Renewable and Sustainable Energy Reviews 14 (2010) 1428–1436

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Assessment of wind energy potential locations in Oman using data from existing weather stations

Sultan AL-Yahyai [a,*], Yassine Charabi [b], Adel Gastli [a], Saleh Al-Alawi [a]

[a] Department of Electrical & Computer Engineering, College of Engineering, Sultan Qaboos University, P.O. 33, Al-Khodh, Muscat-123, Oman

[b] Department of Geography, College of Arts and Social Sciences, Sultan Qaboos University, P.O. 42, Al-Khodh, Muscat-123, Oman

ARTICLE INFO

Article history:
Received 12 August 2008
Accepted 1 January 2010

Keywords:
Oman
Renewable energy
Weather station
Wind energy
Wind profile
Wind turbine

ABSTRACT

This paper analyzes five years hourly wind data from twenty-nine weather stations to identify the potential location for wind energy applications in Oman. Different criteria including theoretical wind power output, vertical profile, turbulence and peak demand fitness were considered to identify the potential locations. Air density and roughness length, which play an important role in the calculation of the wind power density potential, were derived for each station site. Due to the seasonal power demand, a seasonal approach was also introduced to identify the wind potential on different seasons. Finally, a scoring approach was introduced in order to classify the potential sites based on the different factors mentioned above. It is concluded that Qayroon Hyriti, Thumrait, Masirah and Rah Alhad have high wind power potential and that Qayroon Hyriti is the most suitable site for wind power generation.

Contents

1. Introduction

Energy (i.e. heat, electricity and fuel) is an essential element affecting our current living standard. Recently, governments started investigating the wind as an energy resource as well as other renewable resources in order to reduce their geopolitical dependency, enhance their energy security, limit the environmental implication of fossil fuels and control oil price fluctuations.

Oman relies presently 100% on fossil fuel resources (mainly gas) for its power generation. The largest power consumers are the residences. The growing industry sector, with grow rate of 14.4%, is another large power consumer [1]. During the last decades, renewable energy resources have not been given the priority in

* Corresponding author.
E-mail addresses: s.alyahyai@gmail.com (S. AL-Yahyai), yassine@squ.edu.com (Y. Charabi), gastli@squ.edu.om (A. Gastli), saleh@squ.edu.om (S. Al-Alawi).

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doi:10.1016/j.rser.2010.01.008

Oman even though fossil fuel market fluctuation is causing an inability of country economy.

It is only recently that Oman realized the need to explore the renewable energy resources especially solar and wind energies. The Omani government, emphasized the need for more studies and pilot projects on the field of renewable energies before jumping into implementation of large scale power plants from renewable energies such as large wind farms.

Oman has coastlines stretching for more than 1700 km (main land), which ensure the existence of an active movement of the wind along the coastal areas during breeze. On the other hand, the country is affected by both winter and summer monsoonal wind. Both mechanisms ensure the country's sustainable wind energy throughout the year. However, so far wind resources in Oman were not subject to intensive studies and only few research studies were published on this subject.

For instance, the predictability of different weather elements from only nine stations was investigated in [2] using mathematical and statistical models. Wind speed data analysis showed a determination coefficient of 74% which was not as precise as other parameters such as air temperature and surface air pressure. It was just relayed to the larger variability of the monthly averages.

On the other hand, ten-year monthly and annual averages from thirteen stations were used in [3] to investigate the wind energy potential in Oman. According to the published statistics, annual average wind speed of the thirteen stations was 3.67 m/s. Four stations namely (Sur, Thumrait, Masirah, Marmul) had wind speeds above this threshold. Sur and Thumrait with annual average wind speed of around 6 m/s were concluded as being the most promising locations with annual power density of 87.13 and 124.98 W/m^2 respectively. Weibull distribution was used in [4] to analyze five-year monthly/annual means of four stations (Seeb, Salalah, Masirah, Sur). The results showed a good fit of Weibull distribution to the observed data. It showed that both Sur and Masirah had average annual wind speed exceeding 5 m/s and annual wind power density of 222.10 and 167.44 W/m^2, respectively. On the other hand, Seeb had the lowest annual mean power density of 19.52 W/m^2.

Similarly, Al-Ismaili and Probert studied in [5] the prospects for harnessing wind power economically in the Oman. They presented a detailed overview about the possible usage of wind energy. They also discussed different factors considered during the wind energy assessment including financial and environmental aspects. Moreover, they also applied Weibull distribution during their analysis. According to the ten-year collected data (1985–1994) from 12 meteorological stations, Thumrait, Masirah and Sur stations were found to be the most potential locations. Thumrait has the highest yearly mean wind speed of 5.77 m/s (122.5 W/m^2) and both Masirah and Sur follow with mean speed exceeding 5 m/s and wind power densities of 81.69 and 84.65 W/m^2, respectively. On the other hand, Seeb experienced the lowest yearly mean wind speed of 2.52 m/s with no much significant seasonal variation.

The first and the only experimental study of using wind energy in Oman was presented in [6–8]. The study was about water pumping for a research lab situated 70 km north of Thumrait). It was concluded that wind electric pumping system has met the camp's water requirements for more than 80% of the time between April and December 1997. An average pump rate of 3.8 m^3/h was obtained with a wind speed of 3 m/s. The system showed a linear relation between wind speed and water pump output.

Recently, the Authority for Electricity Regulations conducted a study [9] to identify the sources of renewable energy for electricity generation in Oman. The study found a significant potential of renewable energy resources including solar, wind and wave energies. It identified the coastal areas in the southern part of Oman and the mountains north of Salalah as significant wind energy potential locations. On the other hand, it concluded that with the fuel price in 2008, the cost of electricity generated using fossil fuel technology is lower than the cost of electricity produced by renewable energy technologies. The study recommended the implementation of a wind monitoring program in south Oman along the cost and mountains north of Salalah to verify and map wind energy resources.

More recent studies are presented by [10,11]. In [10], electricity generation for Duqm from wind energy was investigated based on the monthly mean wind speed observations. A techno-economic evaluation was also presented using V90-1.8 turbine. It was concluded that the power generation cost is higher than the current existing system, due to the highly subsidized price of natural gas. It was also concluded that the wind power generation can be justified because of the international natural gas prices and the country's long term export obligations. In [10,11], the economics of wind energy was investigated for the research lab presented in [6]. A single 50 kW wind turbine of TekVal was used to demonstrate the economical utilization of the wind energy at the site. It was concluded that the operating cost of the diesel generation was 1.7–1.8 times the specific cost of wind turbine. It was also concluded that the simple payback period of the turbine was about five years.

In this paper, a five-year (2004–2008) hourly wind data for twenty-nine meteorological stations are analyzed. The obtained theoretical wind power was compared to the power calculation using the wind monthly and annual means on the previous studies. Hourly wind data was obtained from the Directorate General of Meteorology and Air Navigation (DGMAN). In this study, station specific value for air density are used compared to single air density (around 1.23 kg/m^3) value used on the previous studies. The air density values are calculated using long term air temperature and air pressure for each station. In addition, due to the seasonal behavior of power demand in Oman, wind power calculation for different seasons is presented. Moreover, vertical wind profiles up to 100 m above the ground are presented. Roughness length values are derived from 7 km resolution interpolated from global dataset used for Numerical Weather Prediction (NWP) at DGMAN. Furthermore, wind speed turbulence intensity is included during the wind potential assessment. Finally, a scoring system to identify the potential sites is introduced.

The rest of the paper is organized as follows. Section 2 gives some background information related to wind characteristics. Section 4 discusses the observational data used in the study and gives wind speed analysis. Wind data processing is discussed in Section 4. Subsections include veridical wind profile, wind power output, turbulence index and diurnal variation and power demand. Section 5 discusses the results and introduces the scoring system used for the assessment of wind potential locations. Finally, Section 6 concludes the paper.

2. Wind characteristic

2.1. Wind power content

The kinetic energy of the wind can be converted into mechanical energy and then electricity using the wind generator or wind turbine. To utilize the full power of the wind, the turbine should be located in a constantly high wind speed area. For wind energy application developers, it is necessary to estimate the future energy production of wind farms. The theoretical power contents of the wind, which does not take into account the energy

losses in the wind turbine itself, can be expressed [12,8] as shown in Eq. (1)

$$P = \frac{1}{2}\rho A u^3 \tag{1}$$

where P is the power (in W), air density ρ (kg/m^3), wind speed u (m/s) and A (m^2) is the area swept by the turbine rotors. For the utilization of the wind power, wind turbine should take as much power from the wind as possible. The ratio of the power used by the turbine to the power content of the wind is called power coefficient. The German physicist Albert Betz calculated the maximum possible power coefficient [13] (Betz limit) to be $C_{p,\mathrm{Betz}} = 16/27 \approx 0.593$.

2.2. Wind power density

From Eq. (1), $(1/2\,\rho u^3)$ is called wind power density (WPD), which combines the effect of a site's wind speed distribution and its dependence on air density and wind speed. Due to the normal variability of the wind speed and the cubic speed relation [14] the WPD should be used for all wind values during the period and not for a single long term average (i.e. monthly and annual). Then the WPD could be rewritten as

$$\mathrm{WPD} = \frac{1}{2n}\sum_{i=1}^{n}\rho u^3 \tag{2}$$

If a single long term average is used to calculate the WPD, then WPD will be underestimated [5,14].

In case monthly means are only available, Energy Pattern Factor (EPF) may be introduced in Eq. (2) to work around the underestimation. EPF is the ratio between the mean of the cubes of each data point divided by the cube of the mean for a series of data [15]

$$\mathrm{EPF} = \frac{1}{n}\cdot\frac{\sum_1^n(\text{monthly mean})^3}{(\text{annual mean})^3} \tag{3}$$

Then, Eq. (1) becomes

$$P = \frac{1}{2}\rho A u^3\,\mathrm{EPF} \tag{4}$$

Air density in the WPD depends on the air temperature and the pressure. If the site pressure is known then the hourly air density with respect to air temperature is

$$\rho = \frac{P}{R}(\mathrm{kg/m^3}) \tag{5}$$

where P (Pa) is the air pressure, R the gas constant for air (287 J kg K) and T is the air temperature in Kelvin (°C + 273.15). For standard atmosphere at sea level (P = 101,325 Pa, T = 15 °C), the air density is ρ = 1.226 kg/m^2.

A major factor for change in density is the change in pressure with elevation. For instance, 1000 m increase in elevation will reduce the pressure by 10%, and, thus, will reduce the power by 10%. If only the elevation is known, the air density can be estimated by Eq. (6)

$$\rho = \rho_0 - (1.194\times10^{-4})z\,(\mathrm{kg/m^2}) \tag{6}$$

where ρ_0 is the air density at the sea level.

2.3. Turbulence intensity

Wind turbulence is the rapid disturbance in the wind speed, direction or vertical component [16]. High turbulence levels may decrease power output and cause extreme loading on wind turbine components [14]. Standard deviation (σ) of wind speed is the most common indicator.

Normalizing σ with the mean wind speed (ν') gives the turbulence intensity (TI).

$$TI = \frac{\sigma}{\nu'} \tag{7}$$

2.4. Vertical wind profile

It is important to ensure the accuracy of the wind data at the level of the turbine blade. Most of the wind speed measurements from meteorological stations are normally installed at 10 m above the ground, but the wind turbines are much higher. Therefore, it is desirable to study the wind speed at different elevations to identify the best height of the wind turbine to be installed.

Wind at higher levels can be calculated using the logarithmic law [17].

$$\nu_2 = \nu_1\frac{\ln(z_2/z_0)}{\ln(z_1/z_0)} \tag{8}$$

where ν_1 is the known wind velocity at height z_1 and ν_2 is predicted wind speed at height z_2; z_0 is the roughness length at the site of interest. z_2 is taken as 0.4 for very rough and uneven terrain.

3. Oman wind data

The DGMAN is the responsible agency for weather monitoring and forecasting. It runs weather stations around the country and archives the hourly data on its database system. DGMAN provides scientists with the available archived data to help them conducting their researches. Fig. 1 shows locations of twenty-nine stations covered on this study. The elevations of the stations above the sea level are shown in Table 1.

Fig. 2 summarizes the annual mean wind speed for all these stations. To study the seasonal behavior, data was grouped into seasons: summer (May–September), autumn (October, November), winter (December–February) and spring (March–April). The seasonal mean wind speed is also shown in Fig. 2. Stations in Fig. 2 are sorted from north to south where Khasab is located at the most north and Mina Salalah at the most south of the country.

The variety of wind mechanisms affecting Oman are clearly represented on the difference on wind observations around the country. All stations in the north down to Sur (except Jabal Shams) have annual wind speed less than 4 m/s. Due to the high elevation of Jabal Shams, the annual wind speed is 4.6 m/s.

On the other hand, all stations bellow Sur (except Adam, Fahud, Salalah, Mina Salalah) have annual wind speed above 4 m/s. Annual wind speed reaches 5.2 m/s in Ras Alhad and 5.8 m/s in Thumrait and Qayroon Hyriti.

During summer, stations bellow Sur are affected by the summer monsoonal flow as shown by the wind rose for summer season in Fig. 3.

Depending of the station orientation and surrounding topography southerly to south westerly flow is dominating the summer. Summer monsoonal flow raise the wind speed at those stations and it is clearly seen that the summer mean wind speed are much higher than the annual wind speed in all stations bellow Sur. During summer the mean wind speed reaches above 6 m/s in Sur, Joba, Duqm, and Qayroon Hyriti, above 6.5 m/s in Ras Alhad and Masirah and reaches 7.5 m/s in Thumrait.

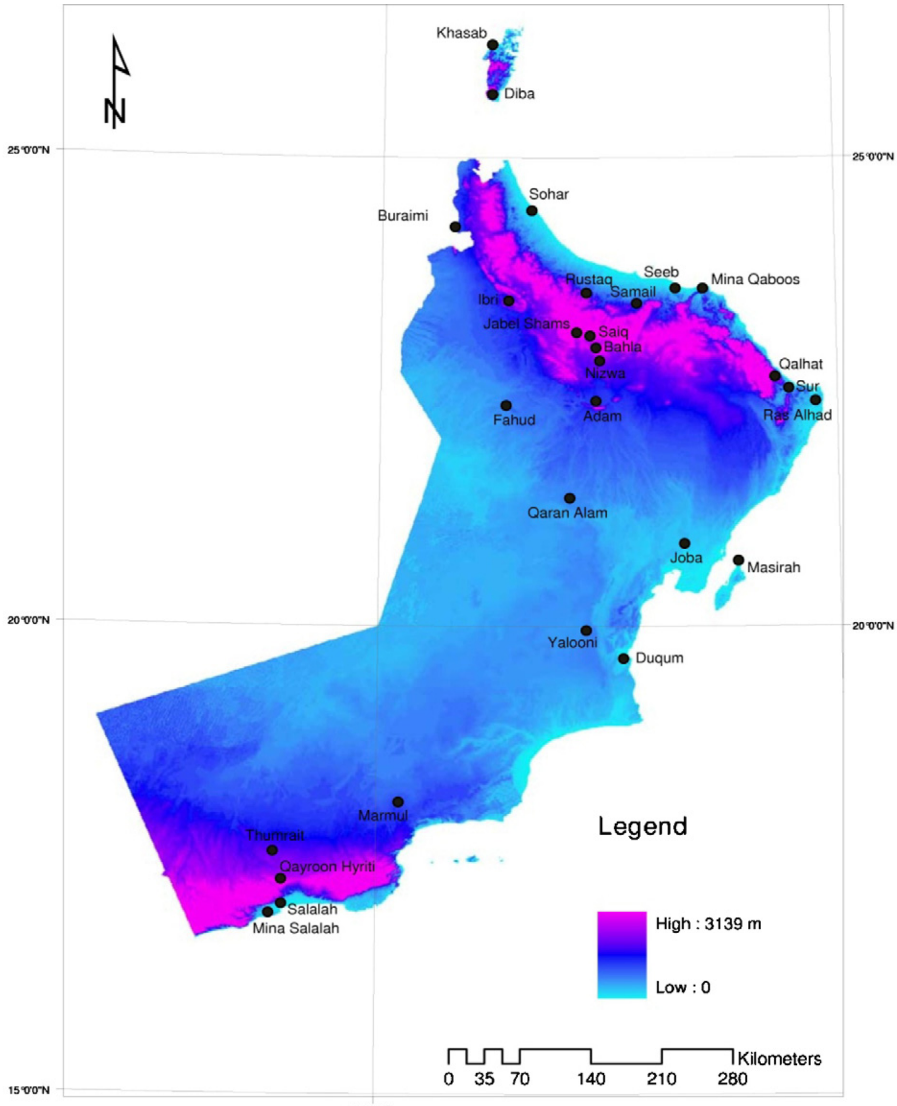

Fig. 1. Location of the meteorological stations use in this study.

Coastal stations in northern part of Oman (i.e. Diba, Sohar in Fig. 4) are affected by the sea breeze during summer while the north to north westerly flow affects the other stations on the northern part of Oman (i.e. Ibri, Jabal Shams in Fig. 4).

Overall, all stations affected by the summer monsoon are subject to higher wind speed compared to the other stations. Summer (monsoon season) and spring (pre-monsoon season) are the windiest seasons in all of the stations.

4. Wind data processing

4.1. Vertical wind profile

Wind speed measurements are taken at 10 m above the ground for meteorological applications. On the other hand, wind energy applications require the wind speed data at the axial height of the turbine because it influences the assessment and the turbine design. Logarithmic law (Eq. (8)) is used to derive the wind speed at

Table 1
Station elevation and roughness length z_0 used in this study.

Station	Elev (m)	z_0 (m)	Station	Elev (m)	z_0 (m)	Station	Elev (m)	z_0 (m)
Khasab	30.36	1.44	Jabal Shams	3008.98	0.98	Joba	46	0.05
Diba	19.81	0.3	Saiq	1754.86	0.27	Masirah	18.8	0.08
Sohar	3.63	0.08	Bahla	598.24	0.09	Yalooni	153.6	0.05
Buraimi	298.89	0.63	Ibra	469.2	0.06	Duqm	4	0.05
Nizwa	459.53	0.08	Qalhat	12	0.64	Marmul	469.9	0.05
Mina Qaboos	4.08	0.01	Sur	31	0.11	Thumrait	466.9	0.05
Seeb	8.40	0.09	Adam	285.09	0.1	Qayroon Hyriti	878.3	0.1
Ibri	249.8	0.05	Ras Alhad	10	0.05	Salalah	20	0.1
Rustaq	322	1.63	Fahud	170	0.07	Mina Salalah	3	0.14
Samail	52.9	0.93	Qaran Alam	139	0.05			

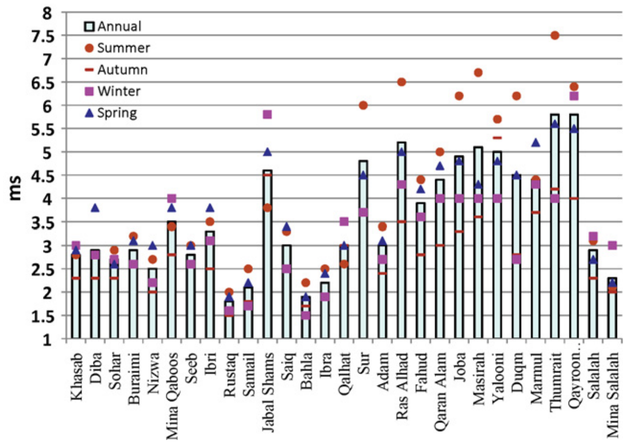

Fig. 2. Annual and seasonal mean wind speed.

different levels by knowing wind speed at 10 m and the roughness length of the site. Due to unavailability of publications to determine the roughness length values for the sites, roughness length z_0 = 0.4 m was used for all stations in [5]. On the other hand, studies in [10,11] used the wind shear power law which is a less accurate approximation [17] to calculate the vertical wind profile.

In this study, to preserve the site characteristics, different roughness length were assigned to each site. Roughness length values were derived from the closest grid point of 7 km resolution dataset (Table 1) interpolated from global dataset used for Numerical Weather Prediction NWP at DGMAN. Fig. 5 shows the vertical wind profile for wind speeds above 6 m/s. Wind speeds less than 6 m/s are not shown in the figure. Different colors represent different height above the ground. The values in the figure are derived from the annual wind speed means at 10 m.

It is clearly seen that wind at few stations is expected to reach above 6 m/s. Khasab, Qarn Alam and Marmul need height of more than 80 m for the wind to reach 6 m/s. For wind speeds above 7 m/s, it needs 90 m at Joba, 80 m at Sur and Yalooni, 60 m at Ras Alhad, 40 m at Thumrait and Jabal Shams and 30 m at Qayroon Hyriti.

However, only three stations (namely Jabal Shams, Thumrait and Qayroon Hyriti) are able to develop wind speeds above 8 m/s at 80 m in Thumrait and at 60 m in both Jabal Shams and Qayroon Hyriti.

Due to the high elevation of Jabal Shams, wind speed can reach values more than 9 m/s at 90 m above the ground while Qayroon Hyriti was limited to 8.7 m/s at 100 m.

Note that there is a positive agreement between the increase in electric power demand during summer and the increase of wind speed during summer in most of the stations. Due to the strong wind during the summer monsoon, higher wind speeds can be reached at lower elevations. Even through some stations such as Fahud was not able to reach 6 m/s at 100 m using the annual wind speed mean, Fahud was able to exceed 6 m/s during summer at 70 m. Table 2 compares the heights above the ground needed to reach 6 m/s using the summer wind speed mean and the annual wind speed mean.

It is noticed that a wind speed of 6 m/s can be reached using the summer mean at 1.5–4 times lower heights than using the annual mean. Notice also that it is 7 times lower in Marmul. Very few locations have the summer mean lower than the annual mean. Jabal Shams is one of them, hence during summer double the height is needed to reach 6 m/s.

4.2. Wind power output

Eq. (2) was used to estimate the wind power density potential. Using single value of monthly or annual means in Eq. (2) will result in an underestimation of the wind power density. To avoid this underestimation hourly data was used during the calculation. All previous studies such as [3–5,10,11] used one single value of monthly and annual means.

Eq. (2) requires air density value which is directly proportional to wind power density potential. Previous studies have used single air density value to all stations, ρ = 1.225 kg/m^3 in [3] and ρ = 1.23 kg/m^3 in [5]. In this study, the air density was calculated as a function of air pressure and air temperature (as shown in Eq. (5)) using long term data. Seasonal air density values were also calculated for all stations. Annual value of air density was used to

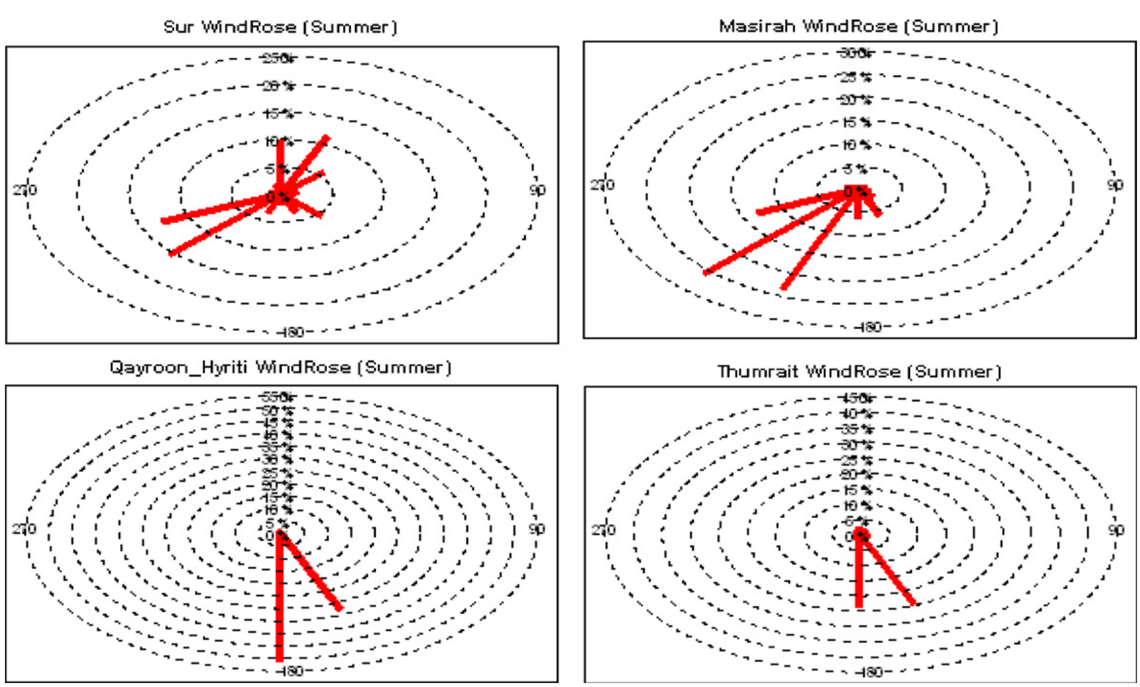

Fig. 3. Wind rose for some of the stations affected by the summer monsoonal flow.

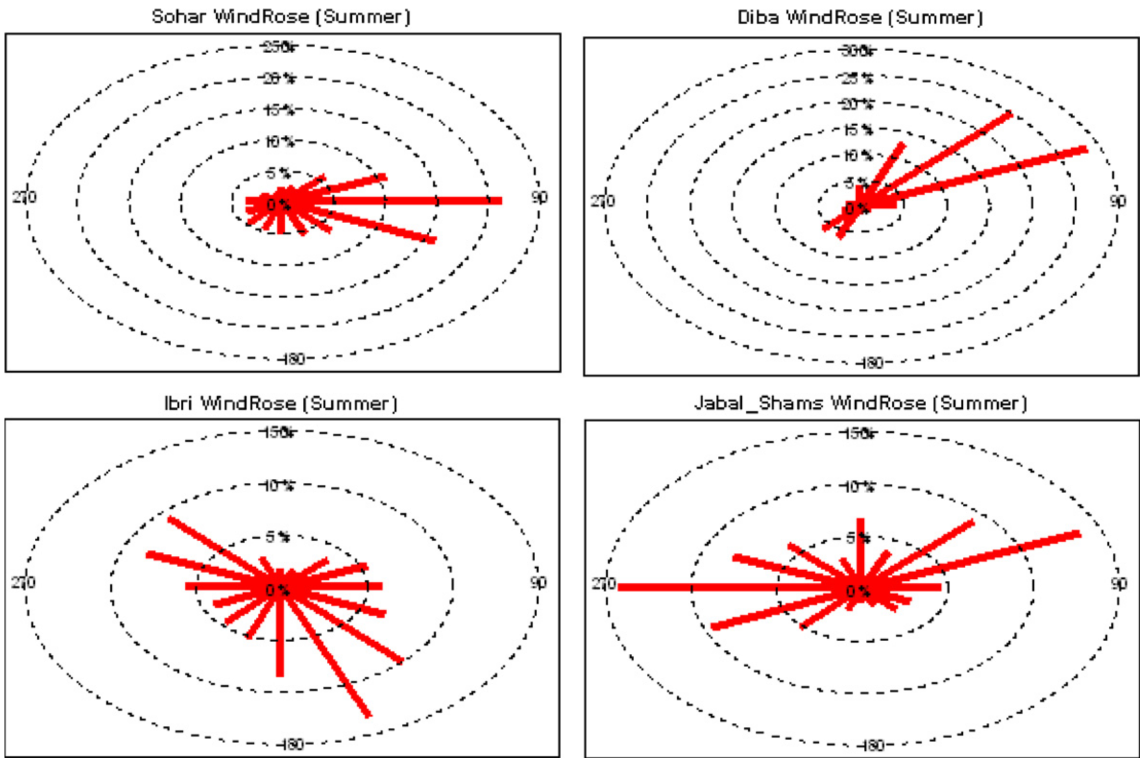

Fig. 4. Wind rose for some of northern part of Oman. Sohar, Diba are affected by sea breeze and Ibri, Jabal Shams are affected by North/North Westerly during summer.

calculate the annual wind power density and the seasonal values have been used to calculate wind power density for each season. Fig. 6 shows the air density values of all stations. It is clear from the chart that all stations have air densities less than 1.2 kg/m^3 except Sur.

Fig. 7 shows the theoretical wind power density output for wind speed data at 10 m above the ground. It shows the annual power density output and the power output for individual seasons. It is clearly seen that few stations have annual theoretical power density above 150 W/m^2. These stations are the stations with annual wind speeds above 4.5 m/s. Only two stations, namely Thumrait and Qayroon Hyriti, have annual wind power densities above 200 W/m^2. The negative effect of air density factor is clearly seen on Jabal Shams compared to Duqm. Jabal Shams has slightly higher annual wind speed than Duqm, but lower power density output because of lower air density. On the other hand, the positive effect of air density is clearly seen at Sur which has the highest air density (1.2 kg/m^3), its power density output is higher than Masirah, Yalooni and Joba which has higher wind speed.

Due to the higher wind speed during the summer monsoon, all stations affected by the summer monsoon have theoretical power density output much higher than the annual power density output. Summer wind power density is about 1.2–1.8 higher than the annual wind power in most of the southern stations and it is about 2.5 higher at Duqm.

Table 3 compares the wind power densities calculated in this study to the wind power densities calculated in previous studies for those stations with high wind power potential.

Notice that wind power densities values calculated in this study are much higher than the values calculated in [3,5]. This is mainly due to the underestimation of wind power density when using one single air density value in Eq. (1). The underestimation is not seen in [4] because authors used the modified power equation (Eq. (4))

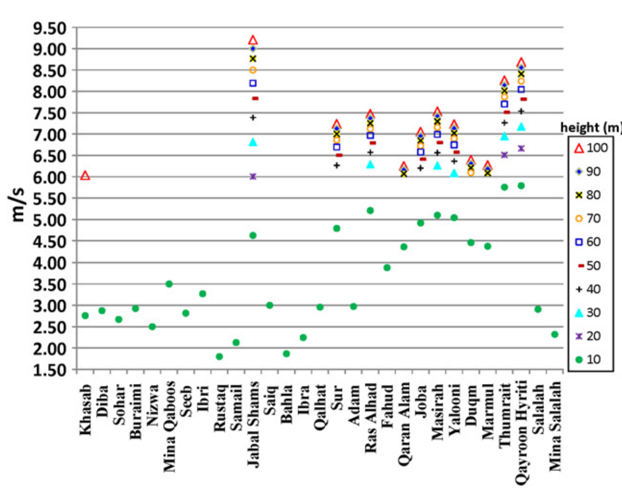

Fig. 5. Vertical wind profile (10–100 m) using 10 m annual mean for wind speed above 6 m/s at heights above or equal 20 m.

Table 2
Heights above the ground (m) to reach wind speed of 6 m/s using the annual wind speed mean and the summer wind speed mean.

Station	Height above the ground to reach 6 m/s	
	Using annual mean	Using summer mean
Khasab	100	100
Jabal Shams	20	40
Sur	40	10
Ras Alhad	30	10
Fahud	–	70
Qaran Alam	80	30
Joba	40	10
Masirah	30	10
Yalooni	30	20
Duqm	70	10
Marmul	80	80
Thumrait	20	10
Qayroon Hyriti	20	10

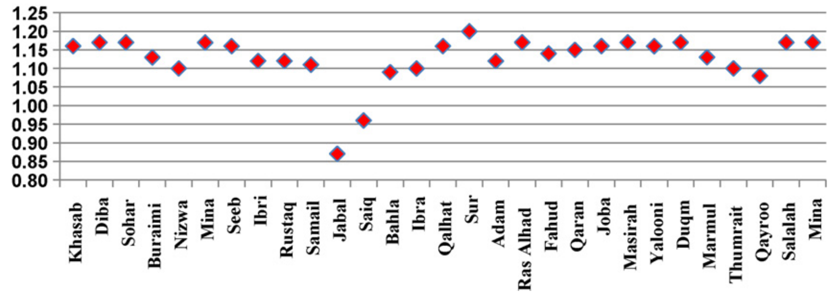

Fig. 6. Calculated air density km/m^3.

with EPF. The slightly higher values calculated in [4] are most likely due to unrepresentative air density value used in that study. It was not possible to check this because authors did not mention the value they used.

Theoretical power density output has also been calculated for different altitudes. The air density values were adapted to different heights according to Eq. (6). Fig. 8 shows the theoretical output for some stations which have significantly higher power density output than the other stations.

From Fig. 8 it can be noticed that all stations at 50 m above the ground (except Jabal Shams and Duqm) can produce more than 400 W/m^2. At 80 m above the ground Qayroon Hyriti and Thumrait can produce around 900 W/m^2 while Yalooni, Masirah and Ras Alhad can produce around 650 W/m^2.

4.3. Turbulence intensity and diurnal variation

Eq. (7) was used to calculate the turbulence intensity for all stations. Fig. 9 shows the annual turbulence intensity values.

From Fig. 9, it can be seen that Qayroon Hyriti has the minimum annual turbulence intensity value of 0.41 and Nizwa has the maximum value of 0.90. The intensities at most of the other locations range between 0.5 and 0.75. Minimum seasonal turbulence intensity was 0.33 at Qayroon Hyriti during summer and maximum seasonal intensity was 1.1 at Nizwa during winter.

It is well known that wind dose not blow continuously at the same speed. This is due to the temperature difference during the day. Site with steady wind flow are the best suited for wind energy applications. Fig. 10 shows the wind variation, which is the difference between daily maximum and minimum and indicate the steadiness of the wind speed.

Notice that Qayroon Hyriti has the minimum daily difference throughout the year. The difference between the maximum and minimum wind speed is less than 2 m/s. On the other hand, Joba has the highest daily wind speed difference of 5 m/s.

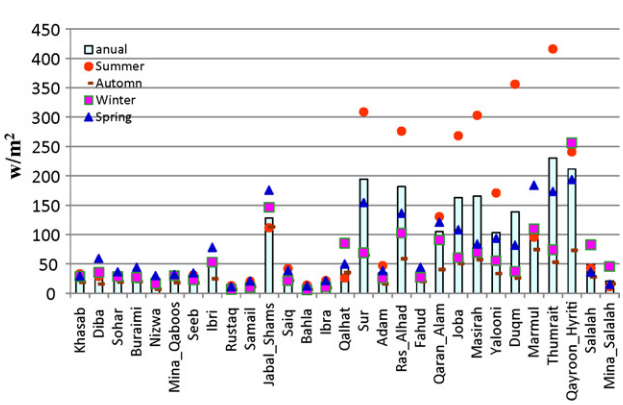

Fig. 7. Theoretical wind power density output (W/m^2) at 10 m.

4.4. Electric power demand

Due to the sub-tropical climate of Oman, annual power demand curve is highly seasonal. The average summer demand is more than double of the average winter demand. The peak demand occurs during July which reflects the high air temperature and the increase usage of air conditioning. Peak hours are typically between 3 and 5 p.m. and again between 11 p.m. and 4 a.m. during summer [1].

Fig. 11 shows the hourly mean wind speed during the summer. Shaded areas represent the day and night peak periods. We can see partial fitting with the peak period for some of the stations and a perfect fit for few other stations.

Unlike Duqm which has maximum wind speed during day peak, Sur's maximum wind speed occurs during night peak and the minimum during the day peak. Maximum wind speed of stations like Ras Alhad and Yalooni occurs outside the peak periods. On the other hand, a station like Qayroon Hyriti has steady wind speed of around 7 m/s during the day period and steady wind speed of about 6 m/s during the night peak.

5. Discussions

Different factors need to be considered during wind energy assessment. Annual wind speed, vertical wind profile, wind

Table 3
Theoretical wind power density calculated from different studies for some of the stations.

	Theoretical wind power (W/m^2)			
	Sur	Masirah	Marmul	Thumrait
Study [3]	87.13	78	65	124.98
Study [4]	222.10	167	–	–
Study [5]	84.65	81.69	69.39	122.50
Present study	194.43	165.5	109.67	230.08

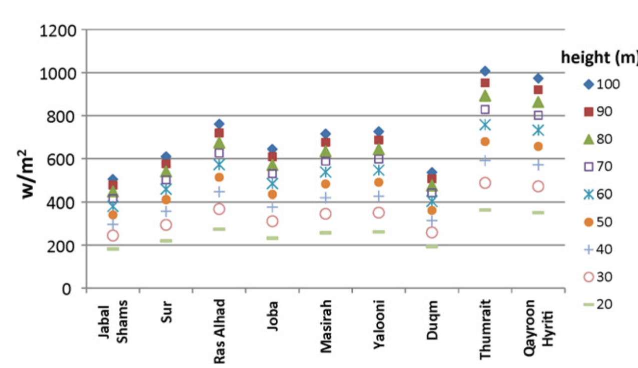

Fig. 8. Theoretical power density output (W/m^2) at different altitudes above the ground for some stations.

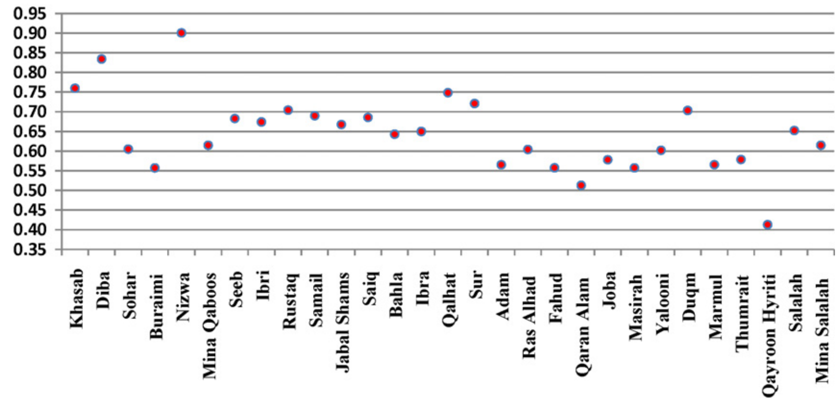

Fig. 9. Turbulence intensity.

turbulence, wind variability, and local peak demand fitness are example of those factors. The distance between the nearest transmission line and the site is also an important factor.

The evaluation of wind energy resources potential using indicators which are based on the wind speed at 10 m and for high speed wind turbine application is listed in Table 4.

Using Table 4, based on the wind energy resources, the classification of Oman weather stations shows that seven stations namely Jabal Shams, Sur, Ras Alhad, Joba, Masirah, Yalooni, Duqm have marginal indicator and only two (Thumrait, Qayroon Hyriti) have good to very good indicators.

Considering those nine stations and for preliminary sorting of the stations, a score is given for each considered factor. Each score rages between 1 and 9, where 9 is the best and 1 is the worse. The aim of this score is to give a preliminary ranking of the sites. More studies need to be carried out to identify the exact weight of each factor and its influence on wind energy. The factors considered in this study are the followings.

Wind power output factor: This factor considers the amount of wind power density output using the annual wind speed mean. This factor is based on the information in Fig. 7. A station with the highest wind power density output is given a score of 9.

Vertical profile factor: This factor considers the vertical wind profile of the station. A station with the highest wind speed at lower elevation is given the highest score. For example, at 40 m above the ground, wind speed at Qayroon Hyriti is 7.54 m/s and at Thumrait is 7.26 m/s, thus, Qayroon Hyriti gets better score than Thumrait. This factor is based on the information in Fig. 5.

Wind speed turbulence factor: This factor considers the wind speed turbulence. Site with lower turbulence intensity is given higher score. This factor is based on the information in Fig. 9.

Wind diurnal variation factor: This factor considers the steadiness of the wind. Site with lower wind diurnal variation is given higher score. This factor is based on the information in Fig. 10.

Peak demand fitness factor: This factor considers the fitness between the wind speed and the power peak demand period. Site's mean wind speed during two peak demand period is calculated. Higher mean wind speed is given higher score. Higher average score means the site has better potential for wind power generation.

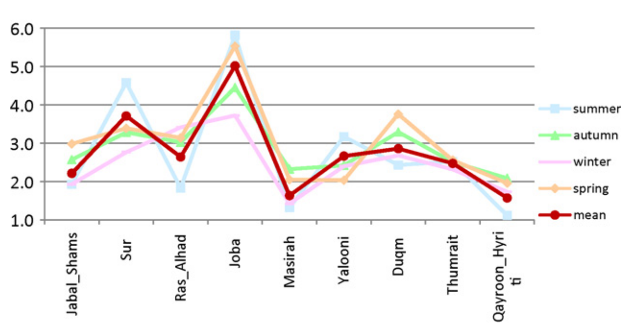

Fig. 10. Daily wind speed variation (max–min) at some of the stations.

Table 5 summarizes the scores for the nine stations with marginal and good to very good wind resource indicators. Stations with poor wind resource indicators were omitted. Higher average score means the site has better potential for wind power generation.

From Table 5, it can be see that the first four best potential sites are Qayroon Hyriti, Thumrait, Masirah and Ras Alhad. Duqm has the least score among the nine stations. Due to the high elevation, Jabal Shams has an accessibility problem which makes it very difficult to transport and install wind turbines.

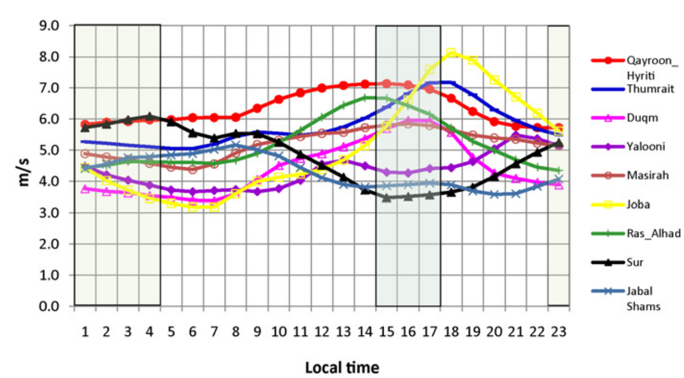

Fig. 11. Hourly mean wind speed at 10 m during summer.

Table 4
Wind resource indicators based on 10 m annual wind speed [18].

Annual mean wind speed at 10 m	Indicated value of wind resource
<4.5 m/s	Poor
4.5–5.4 m/s	Marginal
5.4–6.7 m/s	Good to very good
>6.7 m/s	Exceptional

Table 5
Wind resource indicator scores.

Station	Station classification based on the considered factors					
	Wind power output on high altitudes	Wind speed turbulence	Wind diurnal variation	Peak_1 demand fitness	Peak_2 demand fitness	Average
Qayroon Hyriti	8	9	9	9	9	8.8
Thumrait	8	7	6	8	7	7.2
Masirah	5	8	8	4	6	6.2
Ras Alhad	7	4	5	6	5	5.4
Jabal Shams	1	3	7	2	4	3.4
Yalooni	6	5	4	3	3	4.2
Sur	3	1	2	1	8	3
Joba	4	6	1	7	2	4
Duqm	2	2	3	5	1	2.6

6. Conclusion

Wind data from twenty-nine stations meteorological stations in Oman were analyzed. Stations are scattered from the northern part to the south part of country. Different factors were investigated. These factors include theoretical wind power density output, vertical profile, turbulence and peak demand fitness. Compared to previous studies, the uniqueness of this study is the use of hourly data which highlighted an underestimation of the wind power density potential in the previous studies. Different parameters, namely air density and roughness length which play an important role on the power potential calculation, were derived for each site. Moreover, due to the seasonal power demand, a seasonal approach was also introduced in order to identify the wind potential during different seasons.

After applying a scoring system, it was concluded that Qayroon Hyriti, Thumrait, Masirah and Rah Alhad have high wind power potential while Qayroon Hyriti has the highest.

Excluding Qayroon Hyriti which was not covered on any of the previous studies, and considering the wind power density output factor only, the present results agree with the previous results that Thumrait has the highest wind potential.

Meteorological stations are normally located close to the populated area to serve the civilian purposes. Therefore, it is believed that the available data does not represent the full picture of the wind power potential in the country. Moreover, the distribution of available weather stations has very coarse resolution. Hence, future studies need to enroll high resolution Numerical Weather Prediction output in the wind assessment process. Moreover, more aspects need to be introduced in the assessment such as economical, environmental and geographical aspects (i.e. using of Geographical Information System).

Acknowledgment

The first author gratefully acknowledges DGMAN for providing an hourly data as part of its support for his PhD program at Sultan Qaboos University.

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